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THE SUDBURY LACCOLITHIC SHEET

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INTRODUCTION

The Sudbury mining region has for nearly twenty years attracted the attention of mining engineers and geologists because of its great deposits of nickeliferous sulphides associated with a special eruptive rock. Recent field-work carried out by the writer and his assistants for the Bureau of Mines of Ontario has demonstrated that the region is even more interesting from the geological side than had been supposed; since the ore bodies form part of the edge of a great eruptive sheet having a length of 36 miles, a breadth of 16 miles, and a thickness of a mile and a quarter. While cooling this molten sheet underwent magmatic segregation in which gravitation played a large part, so that the heaviest ingredients, the ores, sank to the lowest points, merging upward into norite, the next heavier rock, which passes upward into granite, the lightest rock of the sheet.

Details of the geology of the region may be found in a final report by the writer recently distributed by the Bureau of Mines;[1] but as many geologists do not receive these reports, it is proposed to give here a condensed account of the nickel-bearing eruptive and its general relationships to the rocks of the region.

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[1] *Bureau of Mines* (Ontario, 1905), Part III.

It was quickly discovered by prospectors for nickel that all the ore deposits are associated with bands of a particular basic rock, at first called diorite, but later found to be norite. The district was mapped in 1890 by Dr. Bell, with Dr. Barlow and other assistants, and their work brought out clearly some of the features just mentioned. Two main bands of the nickel-bearing eruptive were indicated, a northern and a southern, or main, range, running with some interruptions parallel to one another in a northeasterly and southwesterly direction.[1] In 1893 a great advance was made in our knowledge of these relationships by Professor T. L. Walker, who showed that the norite associated with ore passes into micropegmatite, and also that the transition from norite to granite takes place from south to north in the main range, and in the reverse direction in the northern range.[2]

My own field-work, begun in 1902, proved that the two ranges are connected at the ends, forming an irregular oval, and as the results of three summers in the field, the upper and lower boundaries of the sheet were mapped, the only important gap occurring for about two miles at the east end, where the solid rocks are concealed by drift. This work has proved also that the sheet is basin-shaped, since the lower or basic edge everywhere dips inward; and that the ore deposits are all at the lowest points of the basic edge, showing that segregation took place by the aid of gravity.[3]

Dr. Barlow's report, which appeared in 1904, confirms these results as far as the southern range is concerned and gives an exhaustive account of the petrography of the region and the development of the nickel industry. It should be consulted by anyone interested in nickel.[4]

SHAPE AND SIZE OF THE SHEET

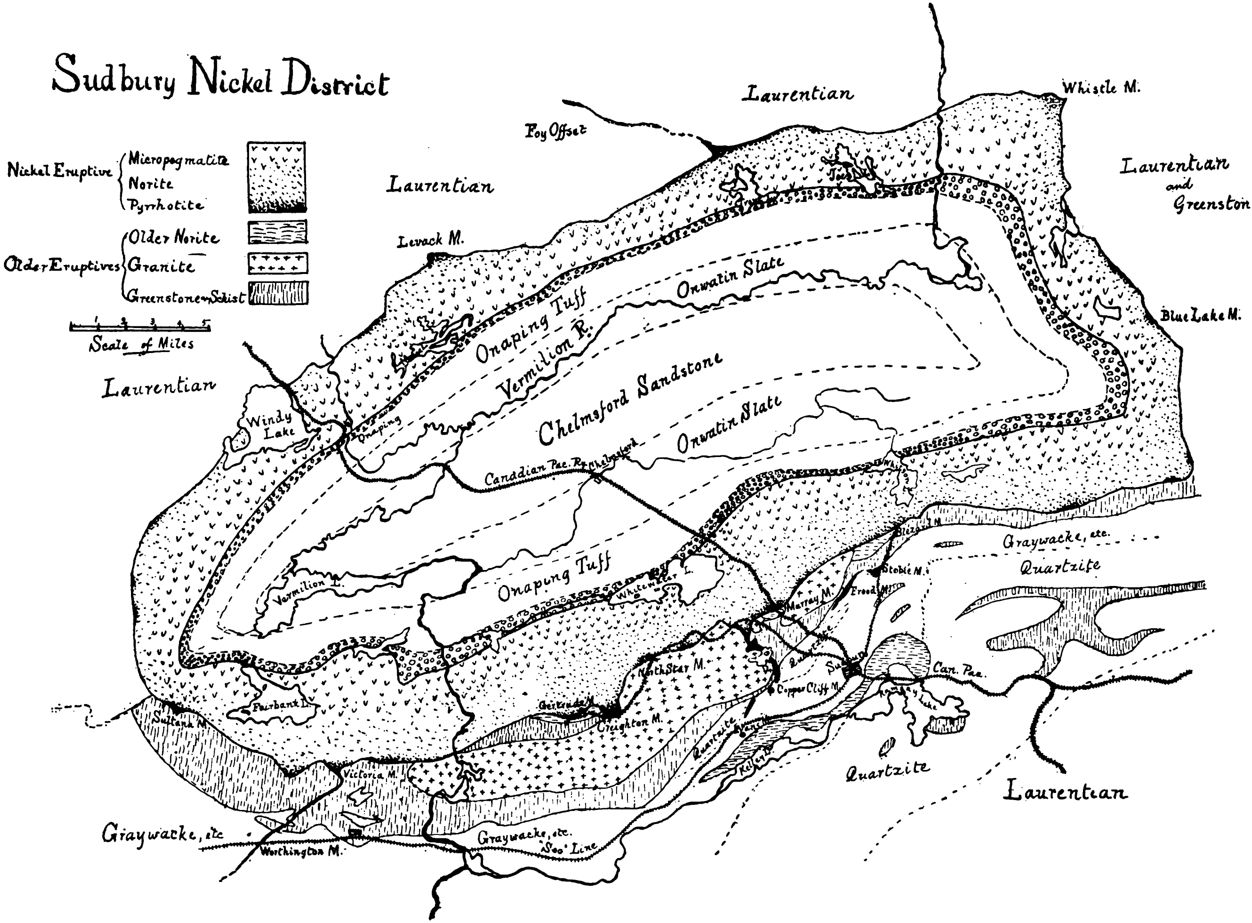
The norite micropegmatite sheet forms an irregular synclinal basin, somewhat boat-shaped or spoon-shaped, to borrow Dr. Daly's

[1] *Geological Survey of Canada*, 1890, Part F.

[2] *Quarterly Journal of the Geological Society of London*, Vol. LIII, pp. 40–46.

[3] *Bureau of Mines*, 1903, pp. 276–78, and 1904, pp. 193, 194.

[4] *Geological Survey of Canada*, 1904, Part H.


Sudbury Nickel District
Nickel Eruptive
Micropegmatite
Norite
Pyrrhotite
Older Eruptives
Older Norite
Granite
Greenstone & Schist
Scale of Miles
1 2 3 4 5
Laurentian
Laurentian
Laurentian
Laurentian
Laurentian and Greenstone
Foy Offset
Whistle M.
Levack M.
Blue Lake M.
Onaping Tuff
Vermilion R.
Onwatin Slate
Chelmsford Sandstone
Onwatin Slate
Onaping
Windy Lake
Canadian Pac. Ry.
Chelmsford
Onaping Tuff
Vermilion L.
Whitewater L.
Whitson
Blezard M.
Graywacke, etc.
Quartzite
Stobie M.
Frood M.
Murray M.
Sudbury
Can. Pac.
Ramsey Lake
North Star M.
Copper Cliff M.
Gertrude M.
Creighton M.
Evans M.
Kelley L.
Quartzite
Quartzite
Fairbank L.
Sultana M.
Victoria M.
Worthington M.
Graywacke, etc.
Graywacke, etc.
"Soo" Line
Laurentian

apt expression, the bowl of the spoon being filled with sedimentary rocks everywhere dipping inward. It rests upon the steeply upturned edges of Huronian schists as well as on Laurentian gneiss and some eruptive masses later than the rocks just mentioned. It is evident that the sheet separates two series of rocks having entirely different attitudes, and that originally the upper sediments rested uncomformably on the lower rocks. In Dr. Daly's "Classification of Igneous Intrusive Bodies" it corresponds to an "interformational laccolith."

As will be seen from the accompanying map, the sheet has an outcrop of irregular width varying from five-sixths of a mile at the narrowest point of the northern range to four and one-fifth miles at the widest part of the main range. The average width is two miles and a half. As exposed at the various mines and prospects the basic edge dips inward, at angles from 20° to 64°; while the sedimentary rocks overlying the sheet have an average dip of about 30°.

Accepting 30° as the correct average dip, the thickness of the sheet is a mile and a quarter. The syncline is 36.2 miles long by 16.6 miles wide, with an average width of 13.6 miles; so that its solid contents must be about 600 cubic miles, if the concealed parts are as thick as the exposed edges.

The upturned edges of the sheet have no doubt undergone great erosion, since the region has been exposed to erosion since Cambrian times. If we suppose that a width of three miles has been removed all around, the original mass must have been 1,000 cubic miles. In magnitude, then, the Sudbury laccolithic sheet far surpasses even the great sills described by Dr. Daly from British Columbia.

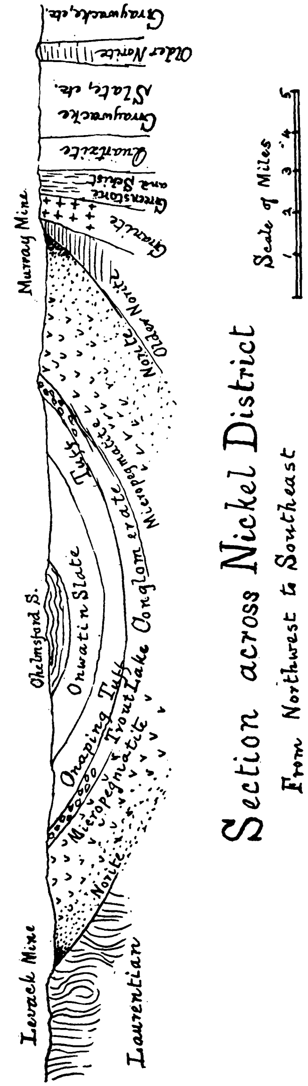
As the term "sill" seems to imply a flat-sided body rather than a curved one, and as sills regularly lie between two layers of sedimentary rock, I have preferred the non-committal term "sheet" for the Sudbury eruptive, which is synclinal and rests on a somewhat irregular surface made up of a complex of schistose and eruptive rocks.

CAUSE OF THE SYNCLINAL FORM

One naturally asks why the eruptive sheet with the overlying sedimentary series should form a synclinal basin. As the surrounding and underlying rocks show hardly any sympathy with this synclinal arrangement, we cannot assume that it is due to lateral mountain building thrusts, but must look for some other cause. The most probable supposition is that the source of the magma was immediately beneath the longer axis of the area, which is now basin-shaped, but was then flat and undisturbed.

The original molten mass was probably much thicker, but also much narrower, than the present laccolithic sheet. When it ascended and spread out widely between the upper sediments and the less regular rocks beneath, there was a collapse, since the schists and older eruptives below had lost their central support. This shows itself very plainly in the shattered and faulted character of the rocks underlying the sheet. The collapse gave rise to the roughly synclinal basin occupied by the eruptive, while the overlying sedimentary rocks settling into the still plastic magma beneath formed a more regular syncline.

The process of collapse and adjustment was probably a very slow one, beginning with the earlier upward movements of the magma, and ending only when the whole mass had cooled so far as to lose its plasticity.



PETROGRAPHY OF THE NICKEL ERUPTIVE

The petrography of this great sheet has been touched on by numerous writers, particularly since Baron von Foullon proved that the fresh rock associated with the nickel ore contains hypersthene instead of hornblende, and is therefore norite and not diorite, as it was named at first. Details of the petrography may be found in

Professor Walker's paper[1] and the reports of Dr. Barlow[2] and the present writer on the nickel region;[3] so that it will be unnecessary to give an elaborate account of the various sections made across the edge of the sheet. In general it may be said that where the outcrop is broad, as near the Creighton and Murray mines, the norite makes up about half of the section; but where the outcrop is narrow, as at some parts of the northern range, the basic portion may be nearly absent. The micropegmatite forming the upper portion of the sheet is more nearly uniform in thickness than the norite beneath The ore deposits, consisting chiefly of pyrrhotite with a comparatively small amount of pentlandite, the real nickel-bearing mineral, and chalcopyrite, are clearly parts of the eruptive and may be looked on as excessively basic phases of the lower edge of the sheet. The ore is not continuous around the whole margin, however, but occupies especially the lowest points, where the outcrop of the eruptive is wide; being largely or entirely absent from narrow parts.

In crossing a wide outcrop of the eruptive, as at the Creighton or the Murray mine on the southern range, one finds on the southeast side massive pyrrhotite resting against granite or lower Huronian rocks and more or less penetrating them as veinlets, or inclosing fragments of them. Even the massive ore contains small portions of the norite minerals, especially labradorite; and a few feet or yards to the northwest the silicates increase in quantity until, when there are about equal amounts of silicates and sulphides, the rock may be called pyrrhotite-norite. Beyond this the sulphides diminish, until within one or two hundred feet there are only blebs of pyrrhotite scattered through the norite; and at length norite without sulphides. From this point for a mile or two northwest the norite undergoes little change, then becomes reddish in color, merging into micropegmatite, which does not vary greatly till the acid edge is reached.

On narrow parts of the northern range true norite is almost absent, and an intermediate rock containing some quartz, orthoclase, and pegmatite forms the bottom of the sheet.

The norite of the basic edge of the eruptive varies considerably from point to point even along the broader parts of the range, but it will be sufficient for our purpose to describe the characters of an average fresh example. It should be remarked that fresh norite is oftenest found close to large ore bodies and may be shotted with particles of ore. On the southern range the rock is dark gray, coarse-grained, with blebs of bluish quartz and large flakes of biotite. On the northern range it is lighter gray, but does not differ in composition.

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[1] *Quarterly Journal of the Geological Society of London,* Vol. LIII, pp. 40–46.

[2] *Geological Survey of Canada,* Vol. XIV, Part H, 1904.

[3] *Bureau of Mines,* Ontario, Vol. XIV, Part III, 1905.

In thin sections the rock is found to contain labradorite to the extent of at least one-half—often more—hypersthene about a quarter, and smaller amounts of monoclinic pyroxene, hornblende, and biotite, with quartz, titaniferous magnetite, apatite, and often sulphides as accessory minerals. The labradorite is usually very fresh, pale brown from dusty inclusions on the southern range, and clear on the northern, with hypidiomorphic forms, sometimes platy. The hypersthene forms rough prisms with good pleochroism, but without scale-like inclusions. The monoclinic pyroxene seems closely related to the hypersthene in appearance, is pleochroic, but has a small or fairly large extinction angle. One is tempted to think of the hypersthene as merely augite with the extinction angle reduced to zero.

Of the minor minerals hornblende occurs mostly as secondary rims about the pyroxenes, while quartz forms small wedges between the feldspars, and occasionally has pegmatitic intergrowths with feldspar.

The typical rock just described is not found everywhere, since usually the ferromagnesian minerals are completely changed to bastite or hornblende accounting for the older designation of the rock as diorite.

At the Creighton mine the norite contains notable amounts of quartz, orthoclase, and microcline, partly intergrown as micropegmatite, but this is unusual. The country rock at this point is gneiss, in general free from micropegmatite, but sometimes showing a rim of coarse pegmatite against the norite, suggesting that the basic magma has interacted with the neighboring rock, perhaps absorbing part of it.

Thin sections of the pyrrhotite-norite found adjoining the ore bodies are often surprisingly fresh, in several of the two dozen slices made, even the hypersthene showing little or no trace of rearrangement. The association of the pyrrhotite and chalcopyrite with the ordinary rock-forming minerals is a matter of some interest, so that the relationships of the two kinds of material in the freshest sections will be described.

The pyrrhotite and chalcopyrite occur generally together, the first being the more common of the two, and they often form sharp-edged masses of a round or angular shape completely inclosed in silicates. They most commonly accompany biotite, which may form a fringe around them, but are rather often found in hypersthene also. In many cases the sulphides lie beside solid portions of magnetite, and in one slide magnetite incloses pyrrhotite.

In the freshest sections there is no hint of a splitting-up or decomposition of the silicates inclosing sulphides, and no visible channel by which the sulphides could arrive at their present position. The edges of the hypersthene prisms are often as square and sharp against pyrrhotite as against any of the silicates of the rock, and the whole appearance suggests a nearly contemporaneous origin of sulphides, oxides, and silicates, the more basic minerals generally keeping together.

In the dikelike offsets from the basic edge of the sheet norite and ore are found mixed, the rock having the same general character as the main range, though finer-grained and more greatly weathered.

The intermediate stages between norite and micropegmatite consist of mixtures of the constituents of the two rocks, but the hypersthene is generally replaced by hornblende.

The acid phase of the sheet is quite variable, but always contains intergrowths of quartz and feldspar. The feldspars include orthoclase and also plagioclases such as andesine, while the dark minerals are hornblende, biotite, and some magnetite, but no pyrrhotite. The micropegmatitic structure ranges from very coarse intergrowths to almost submicroscopic varieties, where a small, sharply outlined crystal of andesine is inclosed in a wide border of plumy intergrowths in which the character of the feldspar cannot be determined even by high powers of the microscope. The feldspars of the acid edge are often platy, giving a hint of trachytic structure, as, for instance, near Onaping. In other cases the rock is more granitoid-looking;

but there are examples near each end of the basin where squeezing and shearing have gone so far as to produce schists. As these are often greenish in color and quite unlike granite or gneiss, they proved very puzzling in the field, but the microscope shows that they consist mainly of plumy micropegmatite with a little chlorite, and an analysis gives a composition similar to the granitic portions of the acid edge, as may be seen from column nine of the table of analyses on a later page.

Judging from its mineralogical composition, most of the acid portion of the eruptive sheet is grano-diorite, but parts of it have so little plagioclase that they might be called granite, while other parts with comparatively little potash feldspar might be called quartz-diorite.

RELATION OF THE BASIC EDGE TO THE ROCKS BELOW

As may be seen from the map, the basic edge of the laccolithic sheet is, in places, quite irregular, with inward projections of the country rock and bays directed outward. From some of the funnel-shaped bays narrow bands of norite reach out into the country rock, sometimes for several miles, but usually with gaps in their continuity. For these projections I have used the term "offset" rather than "dike," since the latter implies a continuous sheet of eruptive rock with somewhat uniform width. One or two of these offsets may be described to bring out the relations of the nickel eruptive to the rocks on which it rests.

Where the country rock extends like a promontory into the basic edge there are no ore bodies, but where the opposite occurs, the norite pushing baylike into the country rock, as at Creighton, large ore bodies are found. When such a bay opens outward into an offset, as at Copper Cliff, the ore forms only small deposits along the sides of the funnel, but larger bodies where interruptions break the offset. In the Copper Cliff offset, for example, we find first a wide bay, with three small masses of ore along its edges; then a narrow band extends southeast for a third of a mile, ending in No. 2 mine, a body of ore 230 feet in length along the offset, and half as wide. This chimney-like deposit has been worked to a depth of 400 feet, and probably goes much deeper.

To the south of this the offset is cut off for a third of a mile, but reappears at the famous Copper Cliff mine, with an ore body 75 to 200 feet in length along the offset and 50 to 90 feet across it, and having a known depth of 1,000 feet. About 700 yards west there is a narrow band of norite with some ore running south for about a quarter of a mile. After another gap of two-thirds of a mile the last outcrop of norite and ore occurs at the Evans mine. The whole length of the offset is more than 4 miles.

It is assumed that all the isolated stretches of norite and ore are either connected by devious channels below the surface, or that they were once connected by portions that have now been eroded away.

One band of norite and ore, that of the Frood and Stobie mines, is of a different kind, showing no point of attachment with the basic edge of the eruptive, but running for 2 miles nearly parallel with it. Here there is probably an underground connection with the main range. The longest offset is from the middle of the northern range, running more than 6 miles to the west.

The basic edge of the nickel eruptive has often a very irregular contact with the rock beneath, frequently inclosing blocks of it and running short distances into it. The offsets are variable in cross-section, and sometimes form curious breccias with blocks of the adjoining rocks, and also of norite of a coarser or finer grain than the matrix. The pyrrhotite takes its part in these relationships very much as the rock does, but it probably remained fluid longer than the norite and has penetrated more intricately into the rock beneath. Often both norite and rock grow finer-grained at the edge, showing that the adjoining rock was colder and chilled the magma in contact with it.

The injection of the magma between the flat-lying upper rocks and the complex of graywacke, schist, and granite beneath occasioned great fracturing and crushing along the lower surface, and in some cases near the southern range there are numerous faults due to the collapse of the rock-floor when no longer supported by the magma which had risen from beneath it. These irregular fractures and faults probably afforded the channels through which the offsets reached their present position.

THE UPPER CONTACT OF THE LACCOLITHIC SHEET

The acid or upper edge of the sheet seems to have caused much less fracturing and fissuring of the rocks in contact with it than the lower edge; but, on the other hand, has exerted a far greater metamorphic action. No long dikes or apophyses are known to project from the acid edge into the overlying rocks, though some short ones have been observed.

The rocks above the laccolithic sheet are the Trout Lake conglomerate with an estimated thickness of 450 feet, the Onaping tuff, 3,800 feet thick, the Onwatin slate, 3,700 feet thick, and the Chelmsford sandstone, 350 feet thick, giving a total of 8,300 feet of sediments.

The lowest of these formations, the Trout Lake conglomerate, which was in direct contact with the upper surface of the molten sheet, has been strongly metamorphosed; and about half of the next higher one, the Onaping tuff, has been greatly indurated and silicified, though its fragmental character is still distinct. The overlying sediments are comparatively soft and unchanged, having a very modern look; while the Trout Lake conglomerate has been so metamorphosed in many places as to suggest a Laurentian gneiss, and was in fact so mapped in earlier days.

The three upper formations are fairly uniform in thickness, but the Trout Lake conglomerate varies from more than 600 feet to only 20 feet, partly perhaps because of original differences in thickness natural to so coarse-textured a rock as a bowlder conglomerate, but partly also, it is believed, because unequal amounts have been absorbed by the underlying eruptive.

The lower part of the conglomerate has been so completely reconstructed that little can be said as to its original composition except that it inclosed large and small bowlders of granite, and that the matrix had a composition which could be transformed into gneiss.

In less altered parts well-rounded pebbles and bowlders of granite, of quartzite, and of green schist or greenstone are found in a grayish crystalline matrix. Occasionally white quartzite is interbedded with the conglomerate.

The exact boundary of the micropegmatite against the conglomerate is very hard to trace. Often in our field-work when crossing the edge of the eruptive toward the sediments, we would overrun the limit, which could be recognized only by the coarser-textured and redder patches representing granite bowlders.

Thin sections made of hand specimens taken across the boundary show first the characteristic micropegmatite of the eruptive itself, afterward changing into micropegmatite of a somewhat ruder kind in the matrix of the conglomerate. Near Moose Lake, for example, on the inner edge of the northern range the micropegmatitic character of the matrix continued for 150 paces from the edge, but had disappeared in the specimen from 180 paces. The conglomerate has been so completely transfused and recrystallized as to be easily taken for an eruptive rock containing some coarser patches, and one can properly call the relation one of gradual transition from the eruptive to the conglomerate.

CHEMICAL COMPOSITION OF THE SHEET

From the microscopic characters of the basic and acid phases of the laccolithic sheet given on a former page it will be anticipated that the chemical composition must vary greatly. These variations were first demonstrated by Professor Walker in his paper on the region, and his analyses will be quoted here with the addition of several made for the Bureau of Mines. In the table given below analyses 1 to 4 are from near the basic edge, 5 and 6 from intermediate points, and 7 to 10 from near the acid edge.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
SiO_2	49.90	51.52	56.89	60.15	64.85	68.48	61.93	67.76	68.95	69.27
Al_2O_3	16.32	19.77	19.39	18.23	11.44	12.70	13.03	14.00	12.74	12.56
Fe_2O_3	......	.47	.38	1.51	2.94	2.41	.56	......	.46	2.89
FeO	13.54	6.77	7.11	6.04	6.02	4.50	8.00	5.18	5.15	4.51
MgO	6.22	6.49	2.11	3.22	1.60	.74	1.76	1.00	1.57	.91
CaO	6.58	8.16	8.11	4.01	3.49	1.41	4.02	4.28	1.72	1.44
Na_2O	1.82	2.66	3.31	1.28	3.92	3.72	3.18	5.22	3.80	3.12
K_2O	2.25	.70	1.04	1.68	3.02	3.36	2.80	1.19	3.28	3.05
H_2O	.76	1.68	1.35	.55	.78	1.13	1.95	1.01	1.50	.76
TiO_2	1.47	1.39	.43	1.34	......	.61	.84	.46	.43	.78
P_2O_5	.17	.10	.11	.23	.24	.20	.32	.19	.20	.06
MnO	trace	trace	.30	.29	trace	.05	.18	trace	.13	trace
BaO	......	......	......	.25	......	......	trace	......	trace	......
SrO	......	......	......	.14	......	......	......	......	......	......
NiO	......	......	......	.17	......	......	......	......	......	......
Cu	......	......	......	.16	......	......	......	......	......	......
S	......	......	......	.54	......	......	......	......	......	......
Total	99.03	99.71	100.53	99.79	98.30	99.31	98.76	100.29	99.93	99.35
Specific gravity	3.026	2.832	2.834	......	2.788	2.673	2.757	2.709	2.694	2.724

In the above table No. 1 and No. 2 are from the basic edge of the southern range near Blezard mine; analyst, Professor T. L. Walker. No. 3 is from the basic edge of the northern range near Onaping; analyst, Mr. E. G. R. Ardagh. No. 4 is from the Creighton mine near the ore body; analyst, Mr. M. T. Culbert. No. 6 is of a syenitic-looking specimen from near the middle of the Onaping section; analyst, Mr. Ardagh; and No. 7 is by the same gentleman, of a greenish-gray specimen from the acid edge at Onaping. No. 8 is from near the acid edge of the Blezard-Whitson lake section; analyst, Professor Walker. No. 9 is from the acid edge on the north shore of Fairbank Lake in the southern range, the rock being dark green-gray and somewhat schistose; analyst, Mr. Ardagh. No. 10 is from near the acid edge of the Blezard-Whitson lake section; analyst, Mr. C. B. Fox.

It should be mentioned that No. 4, from the Creighton mine, is exceptional for the basic edge, containing considerable quartz, microcline, and micropegmatite, perhaps absorbed from the adjoining granitoid gneiss.

The two analyses of specimens taken about half-way between the basic and acid sides of the sheet do not differ greatly in composition from analyses of rock from the acid edge itself, and must be looked on as really belonging to the micropegmatitic side of the eruptive. Averaging the first four analyses as representing the norite, and the last six as representing the micropegmatite, we get the following results:

	Basic Average	Acid Average	Total Average
SiO_2	54.615	66.873	61.970
Al_2O_3	18.437	12.745	15.022
Fe_2O_3	.590	1.543	1.362
FeO	8.365	5.562	6.683
MgO	4.510	1.263	2.542
CaO	6.715	2.727	4.322
Na_2O	2.267	3.827	3.203
K_2O	1.417	2.787	2.239
H_2O	1.085	1.188	1.147
TiO_2	1.157	.502	.763
P_2O_5	.152	.202	.182
MnO	.122	.060	.065
Minor substances	.320	......	......
Total	99.752	99.279	99.500

The total average was obtained on the basis of two parts basic rock to three parts of acid rock, which corresponds roughly to the field relations. The ore deposits, really integral parts of the basic edge, have been left out in the calculation, since the percentage which they form of the whole eruptive is relatively small, though about 2,500,000 tons of ore have already been mined and many millions more are known to exist. Professor Vogt refers to the Sudbury gabbro as containing originally about 0.05 per cent. of the ore, which may serve as a not improbable guess at the quantitative relations.

According to the new classification of eruptive rocks, the average basic side of the eruptive may be called Harzose, and the acid side Adamellose. The norm for the two phases is as follows:

		Basic		Acid	
Quartz		9.24		20.76	
Orthoclase		8.34		22.24	
Albite		19.39	51.92	31.06	37.73
Anorthite		32.53		6.67	
Diopside	$CaO \cdot SiO_2$	....		2.44	3.99
	$MgO \cdot SiO_2$	....		.70	
	$FeO \cdot SiO_2$	....		.85	
Hypersthene	$MgO \cdot SiO_2$	11.30	24.10	2.40	8.74
	$FeO\ SiO_2$	12.80		6.34	

The norm of the rocks as worked out above, omitting minor ingredients, corresponds fairly well with the mode in the norite of the basic side, except that monoclinic augite replaces some of the hypersthene. In the average acid phase of the eruptive pyroxenes hardly occur, being replaced by hornblende and biotite.

CAUSES OF THE DIFFERENTIATION

In my report on the Sudbury nickel region it was suggested that the differentiation of the ore from the rock, and of the norite from the micropegmatite, is mainly due to gravitation. The sulphides are of course far heavier than norite, and the norite is heavier than the micropegmatite; though in the latter case the difference in specific gravity is not so striking. When one observes how the ore has constantly accumulated in the hollows of the floor on which the norite rested, penetrating all the fissures of the rocks beneath, the conclusion seems irresistible that gravity played the main part in its segregation.

There are no ore bodies and hardly any smaller aggregations of ore in the norite above the basal edge; all have settled to the bottom.

The gravitational segregation of rather acid norite from rather basic micropegmatite seems to me on reflection not so certain, though the factor of time is in favor of it. The sediments above the eruptive sheet, without allowing for later erosion, formed a blanket 8,300 feet thick above the molten rock, and the vast mass of the sheet itself, more than 6,500 feet in thickness, must have conduced to excessively slow cooling. There are no certain means of estimating the original temperature nor the rate of cooling; but that the magma was very fluid when it spread out at first is shown by the way it has penetrated all the devious passages of the offsets described on a former page. During the hundreds of thousands of years required for cooling under the conditions mentioned there was time for even slow movements of segregation to accomplish great results.

On the other hand, the theory of stoping should be considered. At the time the field-work was done in the Sudbury region my attention had not been called to this mode of accounting for the micropegmatite, and no observations were made to test its applicability; but the analogous occurrences described by Dr. Daly in southern British Columbia, and his interpretation of Professor Bailey's observations at Pigeon Point on Lake Superior are very suggestive.[1] I have seen no direct evidence of stoping on a large scale from the overlying conglomerate, but have little doubt that the process was to some extent a factor in producing the micropegmatite. The very unequal thickness of the Trout Lake conglomerate from point to point may perhaps be accounted for by unequal stoping.

The peculiar features of the contact, where the boundary between the eruptive and the sediment vanishes, so that there is a real transition between the two, seem better explained by penetration and progressive solution of the conglomerate by the eruptive. It is quite possible, however, that at first much of the conglomerate was stoped away in blocks, sinking deep into the magma and becoming completely digested, while later the eruptive became too viscid to allow blocks to sink, but worked on the overlying rock by heated vapors or solutions, causing the remarkable blending of the eruptive with the conglomerate. As the rock above became heated it would lose in specific gravity, until ultimately it might not have sufficient weight to sink into the magma, which was all the time growing cooler and heavier.

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[1] *American Journal of Science*, Vol. XV (1903), pp. 269 ff.; "The Okanagan Composite Batholith," *Bulletin of the Geological Society of America*, Vol. XVII, pp. 329 ff.; "Differentiation of a Secondary Magma through Gravitative Adjustment," Sonder-Abdruck aus der *Festschrift zum siebzigsten Geburtstage von Harry Rosenbusch.*

Another factor which may be of importance is the gradual change in composition of the upper part of the magma as it absorbed materials richer in silica, whether by digestion of sunken blocks stoped from above, or by direct solution of overlying rocks. It is well known that the more siliceous lavas are much less fluid when near their melting-point than basic lavas, so that the upper part of the sheet may be supposed to have become less and less fluid until blocks could no longer sink through the viscid mass.

It may be that all three processes took part in the differentiation of the eruptive, and that magmatic segregation and the rising of the more acid portions proceeded along with the stoping of blocks and the direct absorption of the overlying rocks.

It is worthy of remark that the micropegmatitic structure is found only in connection with the nickel eruptive; the other acid eruptives of the region are quite free from it. Can it be that micropegmatite is a structure specially belonging to rocks where basic magmas have stoped down and digested or otherwise absorbed more acid rocks? Dr. Daly's sills and the Pigeon Point rocks seem to support this as well as the Sudbury sheet.

EARLIER AND LATER DERIVATIVES OF THE MAGMA

Basic norite.—Though the nickel-bearing eruptive is by far the most important mass of igneous rock in the region, there are several other eruptives that appear to have split off from the same magma at earlier or later times, and these may be more briefly described. They include an older norite which very frequently underlies the nickel-bearing norite, though of a very different type; and certain granites which are intimately associated with the laccolithic sheet.

From point to point for several miles along the southern edge of the main range there is a complex mass of fine-grained norite and greenstone, often with "pillow structure" and amygdaloidal phases, suggesting surface lava flows, which seems to have been an early eruption from the hearth of the nickel-bearing rock. It is, however, far more basic, containing no quartz nor micropegmatite. It is often quite fresh and in thin sections is found to consist of hypersthene or enstatite, a monoclinic pyroxene, plagioclase (bytownite), and magnetite in small equidimensional grains or imperfect crystals. Here again the monoclinic pyroxene is often pleochroic, and all varieties occur linking the monoclinic to the orthorhombic form. The two pyroxenes make up, as a rule, more than half the section, and the magnetite perhaps a twentieth, the rest consisting of short, stout crystals of plagioclase, with two or only a few twin lamellae.

An analysis by Mr. J. A. Horton shows the following results:

SiO_2	46.69
Al_2O_3	14.23
Fe_2O_3	2.00
FeO	12.86
MnO	.11
MgO	8.15
CaO	13.32
Na_2O	.98
P_2O_5	.19
TiO_2	1.28
Moisture	.08
Sulphur	.12
Total	99.97
Specific gravity	3.24

This corresponds normally to the following mineral composition:

Bytownite	42.57
Diopside	25.73
Hypersthene	20.76
Olivine	5.34
Titanic iron ore	4.98
Apatite	.34
Pyrite	.27

It is a percalcic rock of the order Gallare, class Salfemane, subclass Salfemone, and may be named Kedebekase.

It is rather curious that pyrite and not pyrrhotite is found in the older norite, which comes closer to the European nickel-bearing norites than the Sudbury nickel eruptive in chemical composition.

Granite.—Varieties of granite, and granitoid gneiss occur in bands along the southern nickel range or at no great distance from it, and are probably connected with the nickel eruptive in origin, representing a very acid phase in contrast with the very basic norite referred to above. The granites, which should not be confounded with the much older granite and gneiss of the Laurentian, are of two kinds, one coarse-grained and porphyritic, the other medium-grained; and apparently of two ages, the coarser variety being generally older than the nickel eruptive, while the finer-grained variety is distinctly younger, since it sometimes penetrates the norite as dikes or irregularly shaped bodies. The oldest of these granites is later in age than the basic norite, since it has carried off masses of it or of greenstones formed from it.

These acid rocks are normal granites with much quartz and microcline, some microperthite and orthoclase, a little oligoclase, a small amount of biotite, and still less muscovite. No micropegmatite has been found in thin sections of these rocks, a point of contrast with the granite of the acid edge of the nickel eruptive. These granites may have been split off from the general hearth by magmatic segregation without stoping or absorption of more acid materials.

An analysis of one of the later, finer-grained granites by Mr. James Horton gives the following results:

SiO_2	75.62
Al_2O_3	11.02
Fe_2O_3	3.17
FeO	1.29
MnO	.12
MgO	.26
CaO	.58
K_2O	5.33
Na_2O	3.11
TiO_2	.16
H_2O	.10
Total	100.76
Specific gravity	2.59

Calculating the normal minerals we find:

Quartz	35.76
Orthoclase	31.14
Albite	26.20
Anorthite	5.06
Hypersthene	.62
Ferric oxide	.63

Probably some of the soda belongs to the orthoclase, since the extinction angles of the plagioclase correspond to oligoclase. According to the new system the rock may be called Omeoze, a dopotassic, peralkalic rock belonging to the order Brittanare, near the boundary of Columbare.

The basic norite and the acid granites just described are thought to have sprung from the original nickel-bearing magma, because they follow so closely the southern edge of the main nickel range; but it must be admitted that they bear little resemblance to the basic and acid phases of the nickel eruptive itself.

The Ramsay Lake gabbro band.—There are, however, a few bands of gabbro which have some points of likeness to the nickel-bearing norite, though they do not occur in close connection with it. The most notable runs for 9 miles parallel to the southern nickel range as a chain of hills separated from it by 3 or 4 miles of Huronian sediments and earlier or later eruptives.

This irregular band of gabbro has pushed up and sometimes partly overturned the stratified Huronian graywacke around its margin, and a few strips of the Huronian run up its flanks at the widest part, suggesting a chain of elongated laccoliths, or possibly the blunt edge of an eruptive sheet having a nearly vertical attitude. As the gabbro differs markedly from the nickel-bearing norite, it is believed that there is no direct connection between them, but that the southern band probably split off from the magma before the main sheet occupied its present position.

The rock is medium- to coarse-grained and usually greatly weathered, though occasionally fresh enough to show its original composition of labradorite, making up about half the sections, diallage and enstatite, the rhombic pyroxene being in somewhat smaller amounts than the monoclinic. There is a very little quartz in interstices between the plagioclase, and rarely a little micropegmatite. A small amount of pyrrhotite is found at two or three points along the band, but inclosed within the rock, not at one edge as in the main range.

The most interesting feature of this gabbro band is the great white masses of a much more acid rock which are found irregularly along the top of the ridges east of Sudbury and south of Copper Cliff. Some of these masses are 100 yards across and make a very striking contrast with the general green-gray gabbro. They are always inclosed in a margin of very coarse, dark-green hornblende, followed by a zone of mixed hornblende and white feldspar in anhedra several inches across. This phase is succeeded by a zone of white binary granite showing coarse pegmatitic structure, inclosing a central area of almost pure quartz, which may be 50 feet wide.

The hornblende often forms long prisms with a core of white feldspar. The feldspars are oligoclase approaching albite, and orthoclase (or an unstriated plagioclase), and the quartz is glassy, like vein quartz. It is possible that these curious masses, so much richer in silica and alkalies than the rest of the rock, are segregations of the magma separated from the more basic parts somewhat like pegmatite dikes in granite; but they are more probably products of the digestion of large blocks of Huronian quartzite stoped from above. They occur always on the highest points of the gabbro hills.

Very much smaller and less striking masses of a similar kind are found on the basic edge of the main nickel range near Murray mine, close to the bottom of the laccolithic sheet. This fact and the small amounts of pyrrhotite found in the gabbro band just described suggest a relationship between the two rocks. It may be that this gabbro originated in the nickel-bearing magma before segregation had advanced very far, long before the great sheet was injected into its present position.

The three types of rock described above as probably products of differentiation of the main magma, basic norite, acid granite, and intermediate gabbro, were no doubt erupted at very different periods; the gabbro probably coming first, the basic lava flows next, and the granite partly before the ascent of the nickel eruptive and partly after it. None of these rocks occupy areas of more than a few square miles, so that they are insignificant in amount as compared with the nickel-bearing sheet.

Other eruptives.—There is another mass of eruptive materials, the Onaping tuff, consisting of volcanic ash and lapilli, which may be considered as probably having its source in the original magma; though now spread out as a thick layer between the ordinary water-formed sediments overlying the nickel eruptive. As its area is at least 200 square miles and its thickness two-thirds of a mile, its volume must be about 130 cubic miles; and before it underwent erosion it must have been far more extensive than now. Much of its materials fell as angular fragments of glass, now transformed into chalcedony, serpentine, etc., but mingled with the pyroclastic matter there are a good many well-rounded pebbles and bowlders of quartzite and granite, suggesting ordinary water action. Probably the ash fell into the same body of water which deposited the other sediments of the basin.

An analysis of the tuff by Professor Walker gives the following results:

SiO_2	59.93
Al_2O_3	12.12
FeO	10.56
MgO	5.19
CaO	4.49
Na_2O	3.80
K_2O	.97
MnO	trace
Loss by ignition	1.57
Total	98.63

Its composition is somewhat different from the average of the nickel eruptive as given on a former page, but not so different that we cannot suppose it to have come from that source before the laccolithic sheet had reached its present position. The vitrophyre tuff must have been flung from some volcano of which we no longer have a trace, at a distinctly later time than the lava sheets of basic norite described before, since we have reason to believe that the whole series of sediments of which the tuff forms a part extended over the area occupied by the older norite before the sheet of nickel eruptive was injected between them.

In addition to the comparatively large masses of eruptive rock thus far mentioned, there are later dike-rocks penetrating them all impartially, including large dikes of very fresh olivine diabase, which cross norite, ore bodies, granite, and different kinds of Huronian rocks; and a few small dikes of still later granite which cut the olivine diabase, and are therefore the latest rock in the district except the widespread pleistocene beds of clay, sand, and gravel.

The dike-rocks are separated from the older eruptives by a very long interval of time, and may have no connection with the original nickel-bearing magma.

TIME RELATIONS AND CONCLUSIONS

The oldest rocks of the Sudbury district are mainly sedimentary, including small patches of green schist and banded silica of the Iron formation, belonging to the Keewatin; quartzite, graywacke, and slate of the Lower Huronian, associated with certain schists and greenstones; and Middle Huronian graywacke conglomerate in a small area north of Ramsay Lake.

The granite and gneiss mapped as Laurentian penetrate the sedimentary rocks of the Lower Huronian, and so are later in age; but their relation to the Middle Huronian is not known. The basic norite underlying the main nickel range may be later than the Laurentian, though this is not certain, since the two rocks have not been found in contact. It is later than the Lower Huronian, since it incloses blocks of graywacke and quartzite.

Upon the planed-down edges of these older rocks after a great lapse of time the Trout Lake conglomerate was deposited, followed by the eruption of ash and lapilli forming the thick sheet of the Onaping tuff. Next came the quiet deposit of mud forming the Onwatin slate, and of sand, forming the Chelmsford sandstone.

The age of this series of rocks is uncertain, but they have been looked on as probably the equivalents of the western Animikie, now classed as Upper Huronian. Accepting this classification, the sedimentary rocks range from the top of the Keewatin, the oldest known formation, to the Upper Huronian or Animikie. Next came the flood of nickel-bearing magma spreading as a sheet a mile and a quarter thick between the Trout Lake conglomerate and the lower rocks; followed by the collapse of the older rocks because of the removal of the molten mass from beneath, the result of this being the synclinal arrangement of the nickel eruptive and the overlying sediments. Some coarse-grained granite or granitoid gneiss was erupted at about the same time or a little before. Not long after the sheet was spread out and solidified, fine-grained granite pushed up through it or beside it; perhaps the last product of the original magma.

The nickel-bearing sheet and the granites just mentioned were post-Huronian in age, perhaps Cambrian or even Ordovician. When all had cooled and hardened, including even the most fluid part of the magma, the ore in the hollows beneath the sheet, fissures cut across all the rocks and were filled with olivine diabase. Last of all a small supply of acid magma penetrated fissures crossing the diabase dikes. The date of this latest of the granites cannot be determined, since there are no fossiliferous rocks in the region.

From the outline just given it will be seen how long and complex a history there is behind the Sudbury nickel ranges and their associated rocks, including sedimentary rocks of four ages, a great sheet of volcanic ashes, norite or gabbro of three ages, granite of at least three ages, and dikes of diabase; the events beginning with the earliest known period of the earth's history and ending in lower Paleozoic times.

If the inferences suggested regarding the relationships of the eruptive rocks are correct, the same magmatic source has provided medium gabbro, very basic norite, rather acid volcanic ash, coarse-grained granite, somewhat acid norite merging upward into pegmatite and downward into nickel ore, and acid fine-grained granite. Whether the much later dikes of diabase and granite should be placed in the succession is doubtful.

The operations included the formation of coarse-grained plutonic rocks of a stocklike kind, flows of lava showing pillow and amygdaloidal structures, the flinging-out of vitrophyre tuffs mingled with some ordinary sediments, followed by the injection of the vast nickel-bearing sheet and its slow differentiation by gravity and the stoping and absorption of overlying rocks; so that the products of the original magma cooled in part very slowly at great depths, in part somewhat more rapidly as a sheet buried under 8,000 feet of sediments, in part as surface lava flows, and in part as glass fragments due to explosive eruptions. The time required for all these manifestations of activity from the one eruptive hearth extended from the Lower Huronian to the Cambrian or a somewhat later period of the Paleozoic.

Just why the nickel eruptive magma with its great masses of ore and its varied segregation products should occur near Sudbury and nowhere else in the vast Archaean region of northern Canada, there are no means of deciding; but prospectors familiar with the ore and its accompanying rock have looked for them far and wide, but in vain. Pyrrhotite has been found in considerable amounts in other places, but not in association with norite and with only a minute percentage of nickel.

The Sudbury nickel-bearing sheet is unique as far as America is concerned, and far surpasses in magnitude and economic importance the small areas of nickeliferous norite of Scandinavia and other parts of Europe. Its great marginal ore deposits may be compared in size and origin with the segregations of titaniferous magnetite connected with large gabbro areas, and the percentage of iron which they contain would make them valuable ores of iron but for the presence of sulphur.